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The Mars Exploration Rover : an in situ science mission to Mars

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ABSTRACT

In this paper the concept for a mobile vehicle system which performs an in situ science mission to Mars is described. This rover mission with its requirements for driving, positioning at science selected targets, and remote and in situ measurement will utilize the technologies for hazard avoidance and autonomous navigation supported by ground operation tools which use rover-based imagery for position estimation and motion planning.

INTRODUCTION

In July, 2000, NASA announced plans to fly the Mars Exploration Rover (MER) mission, a mission to deploy twins rovers on the surface of Mars in the 2003 opportunity. Each rover's complement of imaging and spectroscopic instruments will be used to determine the compositional and textural diversity of rocks and soils at the landing site. Visible/near-IR and mid-IR spectra will be used to select rock and soil targets that reflect the diversity of material at each site. The rovers will then traverse to these targets and will investigate them in detail with the full instrument set.

The MER missions must meet the following requirements :

- Launch 2 identical rovers (called MERA, MERB) to Mars in the 2003 mission opportunity
- Land on Mars within a latitude band of 5N to 15S (MERA) and within a latitude band of 10N to 10S (MERB).
- The spacecraft shall approach Mars on a trajectory designed to support communications with Earth during EDL through roll stop. The spacecraft shall provide direct communication of data during EDL through roll stop at a rate and volume sufficient to provide for fault reconstruction
- After successful landing, provide vehicle performance data of the entry, descent and landing operations.
- The rovers shall each acquire science data and conduct in-situ analysis for 90 sols.
- The rovers shall be designed to utilize direct-to-Earth X-band communications for surface operations and utilize 2-way UHF communications through the Mars Exploration Project 2001 Orbiter as an operational capability.
- At each landing site operate the following science package: the remote sensing instruments: the Panoramic camera stereo/color imager (Pancam), and the miniature thermal emission spectrometer (miniTES); and the in situ instruments : the Alpha Particle X-ray Spectrometer (APXS), the Moessbauer spectrometer, the microscopic imager and the rock abrasion tool (RAT). The science package also includes a magnet array and calibration targets for the instruments.
- At each landing site acquire:
  - at least one full color and one stereo panoramic image of the site with the Pancam
  - at least one image of freshly exposed Mars rock that is also analyzed by another instrument
  - color and hyperspectral mid-IR panorama images
- Drive the rovers to a total of at least 8 separate locations and use the instrument suite to investigate the context and diversity of the Mars geologic environment
- Operate both rover mission for at least 30 sols simultaneously on the surface of Mars.

- Demonstrate telecommunications capabilities through the Mars Express orbiter
- At least one rover shall demonstrate a total traverse path length of at least 600m with a goal of 1000m.

THE MER MISSION

In implementing the MER mission, the MER project team will use the proven delivery system from the Mars Pathfinder mission (MPF) where the MER rover provides the computing and information system capabilities for the spacecraft throughout the entire mission. The rover computer is connected through I/O interfaces and supporting electronic components to elements of the cruise stage and entry, descent and landing systems. These interfaces are severed as each stage of the mission progresses leading to deployment of a rover on Mars. This resulting rover system is self sufficient conducting the MER science mission, collecting the science data and communicating with the Earth.

The two identical MER missions, MERA and MERB, are planned to be launched on a Delta 7925 and 7925H respectively in the periods of 5/30/03 to 6/16/03 (MERA) and 6/27/03 to 7/17/03 (MERB). Both will fly on Type I trajectories to Mars resulting in constant arrival dates of 1/4/04 (MERA) and 2/8/04 (MERB).

Each spacecraft conducts a cruise mission which establishes a sun pointed spacecraft attitude from a time of approximately 1hr after launch to about 1 hr prior to entry at Mars (see Figure 1). The spacecraft is spin-stabilized (at 2 rpm) with its spin axis pointed toward the sun. The spacecraft uses its sun sensor and star scanners for attitude knowledge and thrusters for attitude control and trajectory correction. For all periods except TCM-1, sun off-angle pointing of the spin axis is restricted to 45deg or less, suited for power generation, and the earth is 45deg or less off the spin axis, suited for direct to earth (DTE) communications through the spacecraft medium gain antenna.

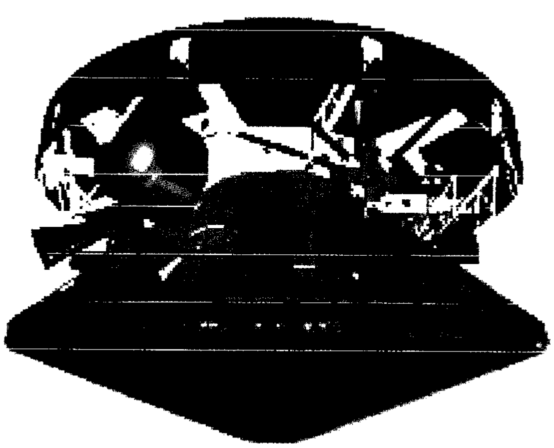

Figure 1 : MER Cruise Configuration

As many as five trajectory correction maneuvers (TCMs) are planned for each spacecraft with the first (TCM-1) conducted about 15 days after launch. The latest (TCM-5) may be performed within 6hrs of entry. During TCM-1, the spacecraft spin axis is allowed to be 90deg off sun point, as the spacecraft is powered by batteries, and 80deg off earth point, as the spacecraft uses its cruise low gain antenna for earth communication.

The spacecraft is turned to entry attitude at Mars about 1hr prior to entry. This places the sun at approximately 90deg off the spin axis. The spacecraft is powered by batteries from this point until deployment on the Mars surface. In a sequence of preparations for the entry and landing events, the heat rejection system (HRS) used throughout cruise is vented, nutation introduced by the turn and the HRS venting is damped by thrusters, lander based equipment is heated and the spacecraft is prepared for separation of the cruise stage. This preparation includes powering off cruise stage electronics and switching antennas to the rover low gain antenna stack. The cruise stage is jettisoned and the entry, descent and landing (EDL) phase of the mission begins.

EDL proceeds in the following steps:

atmospheric entry and deacceleration
parachute deployment
heatshield separation
lander separation on the bridle
radar ground acquisition
airbag inflation
RAD rocket firing
bridle cut

prior to lander touchdown. These activities happen in a sequence of events which occur within approximately 5min after entry. Most events are timed to entry occurrence with only the rocket assist deacceleration (RAD) system firing synchronized to the radar acquisition of the surface of Mars and the calculation of distance to impact. At approximately 10m above the ground, the bridle is cut and landing on the airbags occurs.

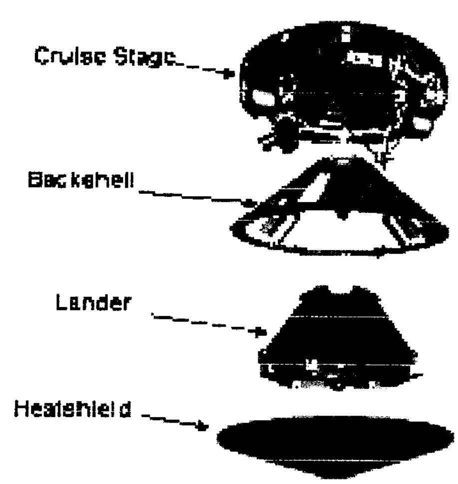

Figure 2 : MER Spacecraft

At touchdown the lander bounces perhaps as many as 10 times and rolls perhaps as far as 1km until it comes to a stop. Thereafter, the lander senses orientation to the Mars gravity vector using the rover IMU and begins airbags retraction. The lander encased within the airbags is a tetrahedron consisting of four petals. Once all or part of the side petal airbags are retracted, the lander opens the three side petals in a sequence which ensures that the base petal down configuration of the lander is achieved. (see Figure 3). The petals are actuated into an 'iron cross' configuration (i.e., all petal surfaces in a plane) suited for subsequent rover deployments.

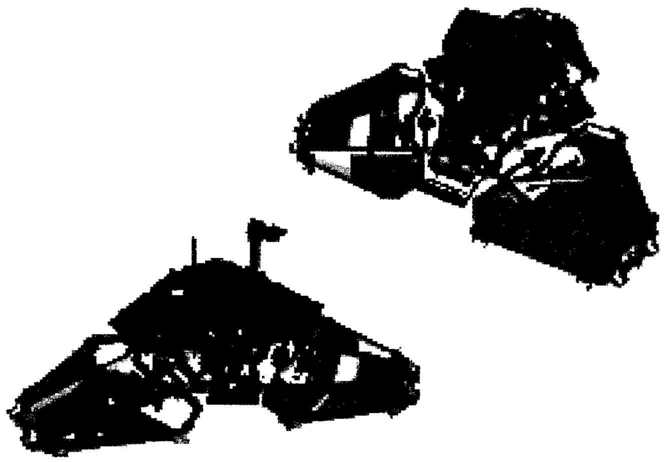

Figure 3 : MER Lander and Rover Deployment

The rover solar panels are then opened, the Pancam mast assembly (PMA) then the high gain antenna (HGA) are released. Each device (PMA followed by HGA) is deployed as MER achieves the 'end of EDL' configuration of the lander and rover.

Throughout EDL, the accomplishment of each significant event (at least those mentioned above) results in the generation of telemetry broadcast direct to earth. Due to the expected earth/mars geometry and spacecraft antenna configurations, this telemetry is limited to frequency shift keys modulating an X-band carrier signal from the transmitter. These so termed 'FSK tones' provide indications in 'real time' received at earth of the accomplishment of EDL events. In addition, it is planned that the Mars Global Surveyor (MGS) orbiter will be positioned to serve as a communication relay orbiter at UHF band during the latter phases of EDL for both MER spacecraft. When the lander is lowered on the bridle, a UHF antenna on the lander is in position to be used to support the transmission of coded telemetry. The MGS spacecraft, equipped with the Mars Balloon Relay communication system, will be capable of receiving these transmissions and relaying the data to earth at a later time. In this fashion, both event accomplishment and engineering telemetry can be available for landing anomaly reconstruction.

The rover upon landing and once achieving its 'end of EDL' configuration has the capability of communicating both at UHF (to the Mars 01 orbiter) or at X-band (direct to earth). The events that follow the achievement of 'end of EDL' configuration include imaging of the lander, rover and landing site providing the first images of Mars and providing the data to select a safe egress direction.

THE MER ROVER

To achieve the MER mission the concept design of the rover and payload is shown in the picture below (see Figure 4 and Figure 6) and described in the following paragraphs.

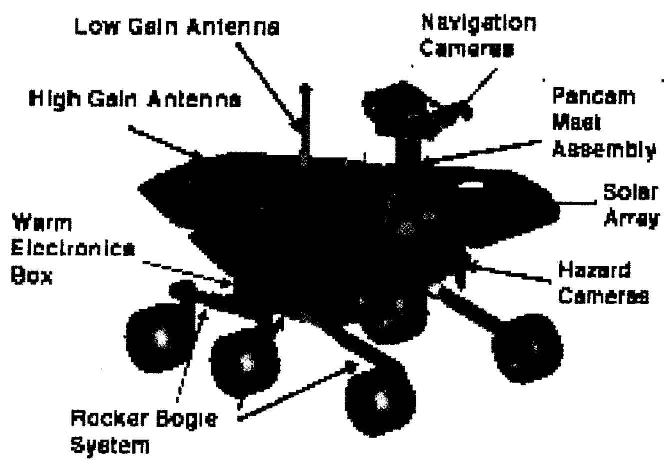

Figure 4 : MER Rover

The MER rover is a 6-wheeled drive, 4-wheeled steered vehicle, 150kg in mass (including science package). At its wheel base, the rover is approximately 141cm long and 122cm wide. At its solar panel the rover is 180cm wide by 167cm long. In its deployed configuration (Pancam mast assembly deployed), the rover is 141cm tall. The rover is stowed on the base petal of the lander in a configuration which allows the petals to fold in a tetrahedral configuration with the rover enclosed for launch and during the cruise-to-Mars phase of the MER mission. In a staged deployment, the rover fires cable-cutting pyros which release tie-downs and allow deployment of the rover solar panels, Pancam mast assembly and high-gain antenna (HGA). Tiedowns of the rover rocker bogie mobility system are released and a staged deployment allows the rocker bogie system to be latched, the rocker system to be actuated and the front wheels deployed, then the rear wheels driven to achieve full mobility system configuration.

In its deployed configuration, the rover is prepared to egress to the surface of Mars. The landing system is designed to accommodate a surface terrain consisting of a rock field of 20% rock coverage or less (MPF landed in a rock field with 16% coverage). However, as a consequence, the lander may be tilted and elevated from the surface. To allow the rover to drive safely from the lander, the rover may need to adjust petals or airbags on the lander and otherwise prepare an egress direction. This is accomplished through actions commanded by the ground system from an assessment of the images and engineering data provided by the rover while on the lander. These actions may include directing the rover to drive on the lander and acquire images in alternate directions. Once the egress direction is picked (or if the rover must drive on the lander and acquire these additional images), the rover cuts its last connections to the lander and deploys to the Mars surface. Once on the Mars surface, the rover begins its surface mission.

This mission will involve driving over the Mars terrain. The rover is designed with a ground clearance of 28cm. The distribution of mass on the vehicle is arranged so that the center of mass is near the pivot point of the rocker bogie system. As a consequence, the vehicle could withstand a tilt of 45deg in any direction without over-turning, although fault-protection limits prevent the vehicle from exceeding tilts of 30deg during traverses. The rover rocker bogie design allows the traversing of obstacles of more than a wheel diameter (25cm) in size. Each wheel has cleats and is independently actuated and geared, providing for climbing in soft sand and scrambling over rocks. The front and rear wheels are independently steered, allowing the vehicle to establish a configuration which allows turn in place with a turning diameter of 194cm. The vehicle has a top speed on flat ground of 5cm/sec. Under autonomous control with hazard avoidance, the vehicle achieves an average speed of 0.6m/min.

The rover is powered by a 6 segment solar panel comprised of 40 strings of 17, 5.5mil 4cm by 6cm GaInP/GaAs/Ge cells. The power system includes 2, 8amp-hr lithium-ion rechargeable batteries, providing (at nominally 28V) up to 448W-hr of energy. The combined panel and battery system allows the rover to draw over 140W of peak power during the surface mission and generate up to 1100Whr energy. The peak panel production is more than 100W (the power required for driving) for 4hr each sol during a summer season on Mars. This power is reduced by the end of the mission to about 600Whr during a sol allowing rover operation with the combined panel and battery system.

Rover components not designed to survive ambient Mars temperatures (-95degC during a Martian night) are contained in the warm electronics box (WEB). The WEB is insulated by solid silica aerogel, is coated with low-emissivity paints, and is heated under a combination of waste heat from electronics, radioisotope heating units (RHUs) and resistive heaters. The thermal design primarily relies on the heat trapped from these sources to maintain internal components above –40degC overnight. Heat soaked out of the WEB overnight biases the system cold and prevents components from exceeding +40degC during the day. There are two exceptions to this basic design : the thermal control of the batteries and the thermal control of the X-band solid state amplifier (SSPA). The batteries are required to be maintained above –20degC for discharge, 0degC for charge and between –30degC and +30degC for survival during all mission phases. This is accomplished through a combination of RHUs packaged with the batteries, thermostatically controlled survival heaters, electronically controlled warmup heaters and a thermal switch connected to a radiator mounted to the –X WEB wall. The thermal switch opens automatically when the temperature of the batteries approaches +30degC, cooling the batteries. The survival heaters powered by the battery activate as the temperature approaches –30degC. The RHUs bias the temperature of the battery assembly above -30degC which is a temperature greater than all other components in the WEB. Finally, in preparation for recharge, the batteries are warmed above 0degC as monitored by battery control electronics (BCBs) . The BCBs (one for each battery) begins warmup of the batteries, as necessary depending on temperature, upon detection of charge. The second exception is the thermal control of the SSPA. This component is attached to a miniature looped-heat-pipe system (LHP). The LHP is intended to transfer heat from the SSPA to a radiator mounted on the –Y WEB wall. The LHP is initiated by a small warmup heater which biases the temperature difference between the ammonia (the fluid of the LHP) external in the radiator and that surrounding the SSPA. Once initiated, at the beginning of X-band transmission, the LHP continues the exchange of ammonia between the radiator and internal loop connected to the SSPA powered by the heating of the SSPA in operation. The transfer of the fluid cools the SSPA, maintaining the component below +40degC. Initial analysis of this thermal design, a combination of passive insulation and active radiative elements shows that all components in the WEB will be maintained to their required flight temperatures throughout the 90sol period of the MER mission.

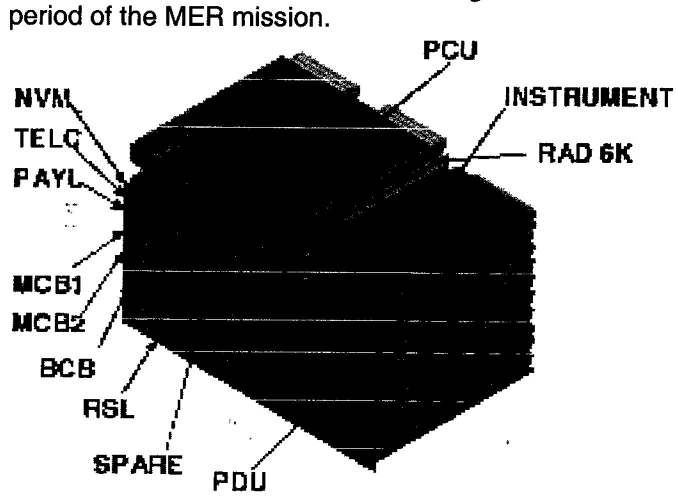

Figure 5 : REM Configuration

Computer control of the rover is provided by a set of computing and power distribution electronics hosted in a

VME backplane architecture. The computer is a 32bit Rad6000 processor with a 20MHz clock rated at 20Mips utilizing a VxWorks operating system. There are four types of memory supporting the processor: 128Mbytes EDAC protected DRAM, 8Mbytes of EEPROM for code storage, 256Mbytes of Flash memory for nonvolatile data storage and selected SRAM supporting component interface functions. The power conditioning and distribution system conditions the nominal 24V to 36V power (from the combined solar array and battery system) to users within the computing system: +5V for logic, cameras and A/D, ±15V for the VME and IMU, 3.3V for FPGAs. The power distribution system also provides for switched power to be supplied to all components (e.g., secondary converters, motors, cameras, payload elements). Computing functions are grouped on a set of boards which plug into the VME backplane and when so packaged are collectively termed the rover equipment module (REM) (see Figure 5). The design allows for convenient integration and test since, once the computer, memory, and power conversion and distribution is installed, other boards may be installed individually thereafter and tested within the system. The computer (RAD6k), memory (NVM), power conversion (PCU) and power distribution (PDU) system are on separate boards in the REM. The NVM also hosts the interfaces for the rover cameras. This interface is pair of a high speed (10Mbps) serial busses between the CCDs of a pair of cameras and SRAM buffers at the NVM. Full images are captured in the SRAM then read-out across the VME to DRAM for processing which can occur asynchronous with subsequent image acquisition and transfer. This interface is MUXd to each of 6 sets of rover cameras. Payload interfaces are provided on the payload board (PAYL). Three 9.6kbps serial interfaces support the command of the miniTES and the command/telemetry interface to the APXS and Moessbauer instruments. A special synchronized serial interface supports 100kbps telemetry from the miniTES. On this board are also 128, 14bit analog –to- digital channels for current and voltage sensors, temperature sensors, and potentiometers distributed on the rover vehicle. Control for up to 40 (36 used) actuators on the rover is provided on two motor control boards (MCBs). Each MCB contains 20 brushed DC motor H-bridge drivers and an FPGA which can provide control for up to 6 motors simultaneously each with quadrature encoder feedback. Together the MCBs can control 12 actuators simultaneously. Also on these boards are interfaces for brushless and stepper motor drivers, completing the collection of actuated elements on the rover and lander. The telecom board (TELC) provides the interface to the rover X-band and UHF transceivers. The mission clock and timing functions are hosted on this board and together with the interface to the X-band transponder (SDST) provides master timing for the rover during the surface mission and for the spacecraft throughout the entire mission. Timing and data interfaces to components external from the rover are provided through remote engineering units (REUs) on the lander and cruise stage. The 1553 bus interface to the REUs is hosted on the TELC board. Battery charge is regulated by the separate battery charger boards (BCBs) which monitor bus voltage, battery temperature and battery state of charge. This board contains separate logic and power interfaces to the battery to manage the battery throughout all mission phases independent of the rover computing system. The instrument board contains logic and power interfaces to operate the APXS and Moessbauer instruments independent of the rover computing system. The last board in the REM is the rover shunt limiter, which is designed to shunt excess power from the arrays.

There are 10 cameras on the rover. All cameras are implemented using a common 1k by 1k CCD chip and associated electronics designed to interface with the rover computing system. Each camera has an application specific set of optics. These cameras are: 2 stereo-capable cameras comprising the Pancam instrument, a pair of stereo-capable cameras to be used for rover navigation (Navcams) mounted on the Pancam mast, 2 pairs of 2 stereo-capable cameras mounted on the +X and –X faces of the rover to be used in hazard avoidance (Hazcams), 1 camera mounted on the instrument deployment device (IDD) to be used with the in situ instruments (microscopic imager), and 1 camera mounted on the gimbal mechanism of the HGA to be used for sun-finding in support of X-band communications (Suncam).

The rover carries an inertial measurement unit (IMU) which provides 3 axis rate and 3 axis tilt information. The IMU is used in rover navigation supporting traverses and in estimating tilt on the surface.

The software in the main computer of the rover, once initiated, executes a control loop which monitors status of the vehicle, checks for the presence of commands to execute, maintains a buffer of telemetry for transmission, performs communication functions and checks the overall health of the rover. This main control loop is tasked to maintain the rover in a power positive, thermally stable and communicative configuration throughout the surface mission. It does so by periodically checking temperatures particularly in the WEB and responding to potential overheating conditions, recording power generation and power storage data throughout the Mars sol, and scheduling and preparing for communication sessions, which involve formating of telemetry data in packets suited for transmission or receiving and decoding commands. Activities such as imaging, driving or instrument operations are performed under commands transmitted in a command sequence to the rover from a ground control station. Each command execution results in the generation of telemetry, which is stored for eventual transmission.

Communication functions on the rover are provided by an X-band transponder with SSPA and a UHF transceiver located in the rover WEB. During the surface mission the X-band transponder is supported by either a high gain antenna (HGA) or a low gain antenna (LGA) mounted on the rover equipment deck (RED). The LGA provides near omnidirectional coverage for both command and low rate telemetry data. Throughout the surface mission, the rover can receive commands at a minimum rate of 7bps and transmit telemetry at 10bps or greater on the LGA. The HGA is a steerable flat panel phased array, which provides for high rate reception of command and transmission of telemetry data. Throughout the surface mission the rover can receive commands at a minimum rate of 250bps and transmit telemetry at 1850bps through the HGA (70m DSN coverage). The UHF system is expected to operate in a relay mode through the Mars 01 orbiter (Odyssey) but is also compatible with the communication protocols of the MGS Mars Balloon Relay system and the Mars Express Orbiter. The system is implemented using a Cincinnati Electronics (CE) transceiver and is designed to be compatible with a like transceiver on Odyssey. The system is supported by a 19cm monopole antenna mounted on the rover –X solar panel. This radio is capable of a rate of 256kbps in telemetry transmission (rover to orbiter) and a rate of 8kbps in command transmission (orbiter to rover). As many as two 6min communication passes per sol by Odyssey can be expected at each of the MER landing sites.

THE MER ROVER PAYLOAD

The MER rover carries a suite of instruments designed to carry out the science objectives of the mission. These instruments provide the remote sensing and in situ measurement resources of the vehicle and are briefly described below (see Figure 6).

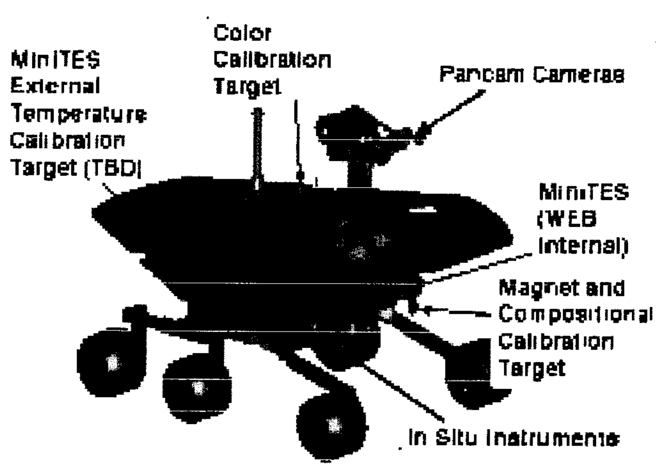

Figure 6 : MER Payload

The Pancam/miniTES instrument is the combination of a mast mounted set of cameras and scan mirrors, and the main miniTES optics, interferometer, detector package and supporting electronics contained inside the WEB.

The Pancam cameras are a stereo capable pair of 1024 x 1024 CCD cameras (format 16.4 deg by 16.4 deg). Angular resolution of these cameras are 0.28 mrad/pixel. The focal length is 43 mm, f/20 with a fixed focus of 1.5 m to infinity. These cameras are mounted behind a pair of filter wheels. Each wheel has 8 filters ranging from a clear (open) slot to colors between 0.4 to 1.0 μm. There are 2 solar imaging filters included. Azimuth and elevation actuators mounted at the bottom and at the top (respectively) of the Pancam/miniTES mast provide a range of 180 deg in elevation by 360 deg in azimuth.

The scan mirror assembly at the head of the Pancam/miniTES mast channels light down the mast to the miniTES optics contained inside the rover WEB. The miniTES is a 6.5-cm Cassegrain telescope, Michelson interferometer, with uncooled pyroelectric DTGS detectors. The miniTES operates in two concentric angular resolution modes : 20 mrad and 8 mrad. The spectral range of the instrument is 6 to 25 μm with resolution of 10 cm^{-1}. The instrument is of fixed focus from 2 m to infinity. The scan mirror assembly has a pointing envelope from +30 deg to -50 deg (relative to the boresight) in elevation. The scan mirror is moved in azimuth using the Pancam mast azimuth actuator with a range of 360 deg.

Four instruments are mounted on a 5 degree-of-freedom instrument arm (see Figure 7). Each can be deployed on a rock or on soil or at a location within a work volume of approximately 0.7m in front of the rover. The instruments on the instrument arm are: the Alpha Particle X-ray Spectrometer (APXS) used for the determination of elemental chemistry; the Moessbauer spectrometer which detects nanophase and amorphous hydrothermal Fe minerals, identifies Fe carbonates, sulfates, nitrates, and determines oxidation state of Fe minerals; the microimager with optics which provides a 30 μm/pixel resolution with 3 mm depth of field and a rock abrasion tool (RAT) which is designed to clear weathering rind and debris from the surface of a rock.

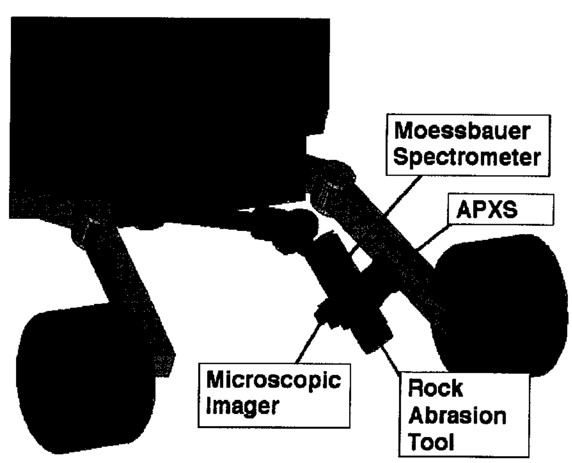

Figure 7 : In Situ Instruments

In operation of this payload on Mars, the rover obtains a color panoramic image using the cameras on the Pancam and a spectral measurement from the miniTES to send to ground operations. An assessment of these images leads to a selection of likely rocks or soil targets for in situ measurement. The rover is commanded to drive to a location and carefully position so that a measurement can be acquired. Once the rover is verified as in position (ground operations team evaluation), the instrument deployment device (IDD) is commanded to place the microscopic imager in contact with a target (rock or soil). The imager is configured with a contact probe preventing damage due to this operation. Once contact is established, an image is acquired. The IDD is moved back along a normal vector to this location and another image is acquired. This is repeated five times resulting in the acquisition of a mosaic of images. Once the image set is completed, the Moessbauer spectrometer is moved into position on the IDD and placed on the same spot as the microimager contact. The Moessbauer measurement is initiated and proceeds for up to 14hr. When completed, the IDD is moved back from the contact condition, the APXS is moved into position, and the APXS is placed on the same spot as contacted by the microimager and Moessbauer. The APXS measurement is initiated and proceeds for up to 10hr. This sequence of three in situ measurements can be repeated on a second location on the target or, if the target is a rock, the surface of the target for measurement can be prepared by the use of the rock abrasion tool (RAT). The RAT is moved into contact with the rock target and removes from the rock a surface approximately 4cm in diameter and a few millimeters deep. This area roughly corresponds to the measurement area of the other in situ instruments (see Figure 8). After a surface is so prepared, the sequence of three in situ measurements can be repeated. The rover can be moved back from the target and remote sensing measurements, high resolution color Pancam images and miniTES spot measurements can be performed. At this point, the rover payload has completed its measurement on this target and is ready to repeat this in situ measurement on another target. If sufficient targets in the immediate vicinity of the rover have been measured (e.g., targets within the panoramas acquired at the beginning of this operation), the rover is ready to move on to another area. The activity flow describe above is repeated: panoramic imaging, driving to a location, position to a target for in situ instrument measurement, and measurement of one or more targets.

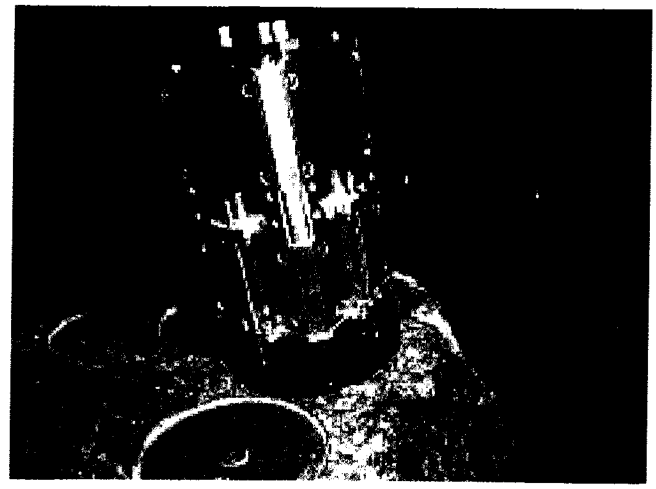

Figure 8 : APXS in proximity to surface prepared by the RAT

This sequence of operation comprises the main payload activities of the MER rover during its 90 sol mission. Additional measurements and supporting calibrations are expected to be performed to properly complete the data sets acquired by the MER payload. A color calibration target is located on the RED and is imaged periodically to compare and contrast with images acquired of the surface. An external temperature calibration target is provided on the rover for use in comparing near/mid-IR measurements made by the miniTES of the surface. A compositional calibration target containing calc-silicate rock material is provided for the APXS and Moessbauer spectrometer.

Additional payload operations are planned to complete the MER payload investigations. A set of magnets are distributed about the rover : on the RED near the color calibration target, on a surface accessible to the IDD and in situ instruments, and on the RAT. The magnet array on the RED can be imaged by the Pancam periodically during the mission and show through spectral measurement contrasting deposition on a strong and weak magnet. The magnets accessible to the IDD based instruments can be measured a few times during the mission by the APXS or Moessbauer spectrometer, providing a compositional measurement of attracted particles. Finally, the magnets on the RAT should attract particles during RAT operation. These magnets can be imaged by the Pancam subsequent to the RAT operation. The miniTES is planned to be used during the mission to measure the atmospheric boundary layers. These measurements collected at approximate 2 hr intervals during a given day will assist in local landing site environment characterization. Lastly, a soil properties measurement is planned. In this experiment a soil patch is excavated by the operation of a rover wheel. Once the wheel is moved out of the patch, the disturbed soil is imaged, a miniTES spectral measurement and a microscopic image are obtained.

HAZARD AVOIDANCE AND NAVIGATION

In its mission the MER rover is expected to drive after landing to a number of sites then to a number of targets within each site for investigation and measurement by the MER payload. In operation, the rover is expected to receive a single command sequence at the beginning of each sol and safely carry out the execution of the commands in this sequence. In executing those commands which move the vehicle, the rover will perform traverses over some distance, precision movements which position itself with respect to targets and deployments of in situ instruments. The following paragraphs describe the capabilities of the vehicle to perform these functions.

When traversing some distance (e.g., more than a few meters) in the Mars terrain, the vehicle will encounter rocks, tilts and drop hazards. To drive safely through such terrain, the rover must detect and avoid hazards while proceeding to its destination. The MER rover does this using a variation of the 'go_to_waypoint' command construct used on the 'Sojourner' vehicle during the Mars Pathfinder mission (see references 1 and 2). The hazard avoidance and navigation capability required to perform such a command are tailored for the more capable MER rover vehicle.

The 'go_to_waypoint' command contains a coordinate parameter giving distance and heading of the intended destination of the vehicle, a tolerance of accepted distance near the destination, a distance which quantifies missing the target and a timeout parameter for completion of the drive. In executing the command the rover must both navigate autonomously and perform the drive avoiding hazards along the route. The rover performs hazard detection using the pair of Hazcam cameras either at the +X or –X face of the vehicle. While the rover is stopped, an image from these cameras is captured and processed, using the camera models, into a set of (x,y,z) coordinate points in front of the rover. This resulting map of points is processed into a set of terrain features (steps, slopes, roughness) which serve as a model of the actual terrain in front of the vehicle. This model is used to determine if the terrain features represent obstacles for the rover (e.g., a feature with height of 20cm or greater will be considered an obstacle). A small number of short potential paths in the direction to the destination are developed within this model and a safe path avoiding obstacles is chosen. The rover is moved a short distance (about 30cm) along this path and the process is repeated. As the terrain models are acquired, they are organized into a 'world' model with the rover at the center of approximately a 10m by 10m area. Once constructed, this larger model provides more options for safe traverse to the destination and prevents the rover from encountering obstacles already avoided during prior segments of the drive. It also can be used to provide a more complete hazard assessment model for evaluation once the rover has moved a certain distance (e.g., allow the rover to determine if extended portions (solar panel segments) of the structure intersect portions of the terrain). The rover proceeds to move to the destination until the tolerance of accepted distance near the destination is achieved or (in failure cases) either the rover has driven a distance further than the target or for a time which exceeds that accepted for the traverse.

Each time the rover stops during the drive, an assessment is made of the location of the rover. The rover computes distance traversed using an average of wheel encoder counts. The encoders on each wheel provide about 4000 counts per revolution. The quadrature design of the encoders accounts for forward and backward wheel motions. Changes in heading during the drive are determine by the integration of the signal from the IMU. Periodically, while the rover is stopped, the camera used as a sun sensor can be assessed to determine the sun angle. This measurement (developed using the on-board clock and sun angle predictions) corrects for drift developed during the drive in the measurement from the IMU. Finally, to correct this measurement of heading for the terrain induced tilt of the vehicle, the set of accelerometers of the IMU, one accelerometer aligned to each vehicle axis, measures inclination with respect to the gravity vector.

One additional position estimation technique employed during the traverse is a measurement of 'progress' as can be assessed from the change in the relative position of the same terrain feature as the rover moves from one position to another. This 'progress' is estimated through a maximum likelihood estimate of the changes in feature position which is then fed back into the rover position estimate. This process called visual odometry helps to account for slippage and (to some extent) sinkage which are not measured otherwise on-board the vehicle.

Precision movements which position the vehicle with respect to targets are commanded from the ground operations team using an assessment of the image set (Navcam and Hazcam images) sent from the rover. These movements are defined in terms of forward/backward drives of 1 or 2 meters and turns which present a target in the workvolume of the IDD. In this same set of images, the IDD motion is planned to the target. A position and normal vector of approach to the target is developed for an in situ instrument. The necessary stow/unstow, rotate to position and approach vectors are commanded to the vehicle by the ground operations team.

PLANNING

Planning for rover traverses and for rover operations in general is primarily a ground station directed activity. This activity is modeled on the ground operation planning performed during the "Sojourner" mission [see references 3 and 4]. The assessment of imaging and spectrometric measurements performed by the science team will lead to the determination of which locations at the landing site are suited for in situ measurement. Since these locations are positions within a (usually stereoscopic) image transmitted by the rover, locations can be commanded to the rover in the coordinate frame of this same stereo image. Traverse planning can be performed based on an assessment of the terrain within that stereo image or a larger stereo image set. An operator can design the traverse at a rover control workstation by 'flying' a 3-D rover icon through the image display. By inspecting the stereo scene, as well as placing the rover icon in various positions within the scene, the operator can assess the trafficability of the terrain. Long distance traverse planning can be performed in this way by accumulating waypoints which avoid obstacles and direct the rover to the destinations of interest. This process results in the generation of a sequence of movement commands to be eventually performed by the rover. These commands are captured in a command sequence which is then planned to be sent to the rover for execution.

Other sequences which plan for science operations are developed at these control workstations. Instrument operations for the Pancam and miniTES and for the IDD instruments can be planned and prepared for transmission then execution on the rover.

CONCLUSION

The MER spacecraft is designed to deliver a capable rover to the surface of Mars for the accomplishment of a remote sensing and in situ measurement mission. The MER rover is a concept mobile vehicle for conducting this mission. In accomplishing its mission, the rover must drive with precision to a commanded location, position precisely over a target site and collect measurement data from its payload. This data in the form of imaging and spectral data is transmitted back to earth and is used there by the ground operation team to plan subsequent motion and operation of the vehicle.

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ACRONYMS

APXS: Alpha Particle X-ray Spectrometer
CCD: Charge Coupled Device
DRAM: Dynamic Random Access Memory
EDL: Entry, Descent and Landing
EEPROM: Electrically Erasable Programmable Read Only Memory
FPGA: Field Programmable Gate Array
Hazcam : Hazard Avoidance Camera
HGA : High Gain Antenna
HRS: Heat Rejection system
IMU: Inertial Measurement Unit
IDD : In situ instrument Deployment Device
LGA: Low Gain Antenna
LHP: Looped Heat Pipe
MCB : Motor Control Board
MERA : Mars Exploration Rover, 1st mission
MERB : Mars Exploration Rover, 2nd mission
MGS : Mars Global Surveyor
miniTES: Miniature Thermal Emissions Spectrometer
NVM: Non-Volatile Memory Board
Navcam : Navigation camera
Pancam : Panoramic camera
PCU: Power Control Unit
PDU: Power Distribution Unit
RAD: Rocket assist deacceleration
RAT : Rock Abrasion Tool
RED : Rover Equipment Deck
REM: Rover Electronics Module
REU: Remote Engineering Unit
RHU: Radioisotope Heating Unit
PAYL: Payload Board
PMA: Pancam Mast Assembly
SDST: Small Deep Space Transponder
SRAM: Static Random Access Memory
SSPA : Solid State Power Amplifier
Suncam : Sun Angle measurement camera
TCM: Trajectory Correction Maneuver
TELC : Telecom Control Board
WEB: Warm Electronics Box